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THE DEVELOPMENT OF WIND POWER INSTALLATIONS FOR ELECTRICAL POWER GENERATION IN GERMANY

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16. Abstract

Windmills are gradually disappearing from the landscape of Northwest Europe. The development of installations for reducing electrical energy from wind energy is also beginning in Germany. The wind tower generation installations built by German firms have a wheel area of between 50 to 250 m^2 for installed power levels between 3 and 50 kW. In the last 30 years, there has been a tendency to increase the design rotation rate coefficient from 2-4 to a level between 8-16. At the present time, there are reliable installations with nominal power levels between 3 and 22 kW. Successful Danish, American, Russian, French and German experiments over prolonged time periods proved that it is possible to operate wind power generation units in parallel with public high-voltage installations without any difficulty. This means that wind energy is now available to satisfy the energy requirement which is continuously increasing all over the world. A rough calculation shows that the energy capacity of the ocean of air is unlimited.

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THE DEVELOPMENT OF WIND POWER INSTALLATIONS FOR ELECTRICAL POWER GENERATION IN GERMANY.

Ulrich Hütter *

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The First Wind Motors

The discovery of the internal combustion engine and the growth of the public electrical networks caused approximately 27,000 large windmills to disappear over a period of 20 years. These windmills in Holland, Denmark and North Germany had ground almost the entire wheat crop at the turn of the century. Between the years 1900-1930, 8 - 10 average size and small wind turbine plants [1], particularly in Saxonia and Schleswig/Holstein produced approximately 3600 steel wind turbines for driving electric current generators and water pumps. These were built according to American design. After a short increase, the numbers of devices manufactured dropped off beginning in 1912, until finally all factories in Germany ceased to build these machines.

The many-blade sheet metal turbines first shown at the World Exhibition in Philadelphia in 1876 had relatively small areas swept out by the turbine wheels (60 t0 30 m^2). These represented a step backward compared with the windmills which had been developed over many centuries. The windmills have

* Kirchheim/Teck

** Numbers in the margin indicate pagination of original foreign text.

larger specific rotation rates and have many blades. The diameter extends from between 8-24 meters. The circular areas swept out by the blades varies in the range between 250 to 450 m^2. Later on they were extensively used all over the world for water supply for farmers and in particularly in semi-arid plain areas. Under certain conditions, wind motors can be used for certain limited purposes. Nevertheless, no progress was made during the 75 years of development during the technical era.

According to the agricultural college at Glenn near Bloemfontain, 77,000 small wind pumps were used on farms within the South African Union, which demonstrates the extensive use of these devices. Many farms have several such wind motors in order to lift as much water to the surface as possible.

Fast rotating machines, in which the ratio of the tip velocity to the velocity of the undisturbed wind (rotation rate coefficient) amounts to 6 - 8, have up to the present primarily been built in the United States for driving low voltage electrical generators. They have small dimensions (wheel area 7 to 18 m^2). The so-called wind chargers were developed as charging devices for batteries used in radios. There are a few hundred thousand such machines distributed all over the world. The users of these small installations soon began to operate the battery charger devices for illuminating the houses and operating small appliances. However, it is hardly possible to completely supply medium sized farms using devices of this size, unless unusual wind conditions prevail.

As the size of the installation is increased, the forces, moving masses, incident flow non-uniformity and therefore the requirements for adjustment accuracy increased. Also the con- /3
trol requirements and the control program requirements increased as to the requirements for quiet operation. This means that

a completely different and therefore completely new class of device must be developed as a result of a systematic development, which can then satisfy all requirements.

The development of wind force installations in Germany up to 1945.

In Germany it was soon recognized that the wind energy only has possibilities of contributing a substantial amount to the energy supply if the installations to be developed were not substantially smaller than the old windmills.

Using the new aerodynamic knowledge for aircraft wings, K. Bilau wanted to save the windmills not yet destroyed during the first World War, as well as the windmills converted for motor operation. By covering the so-called blade poles with streamlined sheet metal coverings, he was able to increase the power coefficient of all windmills by more than 60%. He also increased the rotation rate coefficient from 1.7 to 3.5, that is, by 106% [2]. However, this led to the problem of a much more rapid control system than was available in the existing windmills. He was first unsuccessful when he used wheels braced by rotatable tangential perturbation surfaces. He finally developed the rotatable rear part shown in Figure 1. These members can be rotated around an axis parallel to the longitudinal blade axis. The solution proved itself and made it possible to maintain several old windmills. Bilau built wind force test stations on a farm in East Prussia and later on in South England. There he carried out tests with new wind motors which had steel tube towers and wheels having rotation rate coefficients between 3 and 4.5.

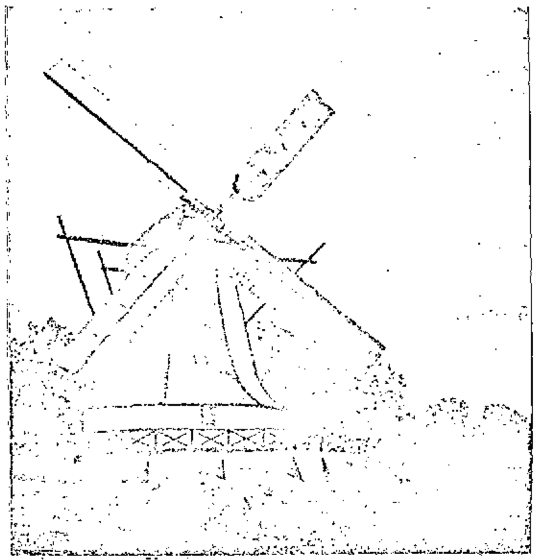

Figure 1. Dutch windmill. Two of the blades have Bilau ventilating edges and rotatable rear part for control purposes.

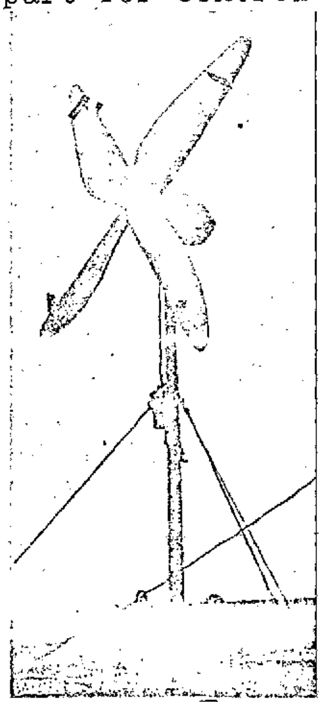

Figure 2. Nine-meter diameter electrical test installation of K Bilau, 1924. Rotation rate coefficient 3-4.

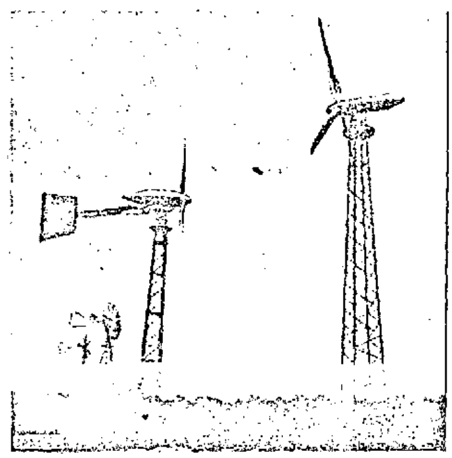

Figure 3. Test field of the Ventimotor GmbH, Weimar. From right to left: Completely electrically controlled 10 kW direct current installation (10 m diameter).
Mechanically controlled 50 kW installation (18 m diameter)
Steel wind installation for parallel run experiments (7.2 m diameter)
Köster installation for water pumping (7 m diameter).

The devices built by Bilau and all new machines have many common features. There was a streamlined gondola installed so it could be rotated on a steel tube tower which was held by means of steel cables. The gondola contained the gear transmission and the power generator. It is shown in Figure 2. Unfortunately, there was no industrial production of the Bilau devices, which had a diameter between 8 and 12 meters. The reason for this is probably the difficulties associated with the strength of the rapidly rotating blades, as well as problems associated with the electrical installation.

Using Bilau as an adviser, the firm Ventimotor GmbH in Weimar wanted to develop wind force installations for producing electrical current and for pumping water. Proven prototypes of the usual design, primarily the design of Stahlwind, Dresden and Köster, Heide/Holstein, were built in a large test installation for wind force devices which was well equipped. In addition, small wind chargers made by Dutch and American firms were tested. After the company had existed one year, it was able to develop and test its own versions of wind wheels using the available towers. Also wind tunnels were used. By using wheels with new shapes and profiles, it was possible to achieve efficiencies which were more favorable than any other known from the literature.

A 10-meter wheel diameter installation was equipped with a purely electrical control system [3]. A 7-meter wheel diameter installation was operated for a whole year in parallel with the public electrical network of the City of Weimar. At the end of the war in 1945, six wind tunnel installations, shown in Figure 3, were operating on the test area. The largest had a wheel diameter of 18 meters, a rotation rate coefficient of six and a tower height of 30 meters, and installed power level of 15 kW [4]. A project for a 40-meter wheel diameter installation and a power output of 500 kW was in preparation which was to have been established in the Thüringer forest. /4

Engineers at the Ventimotor GmbH after the war continued their work at the Allgaier firm in Uhingen and at the Firm Pleuger in Hamburg where they developed wind force installations.

The work on wind force installations was also carried out at the Firm Porsche KG in Stuttgart-Zuffenhausen in the year 1940. A two-blade test wind wheel having a rotor diameter of 3.4 meters was instituted for propulsion and propulsion motors in Stuttgart on the most appropriate design of wings and protection devices against storms. A four-blade wheel having a diameter of 7.2 meters was tested at the Agricultural University at Stuttgart-Hohenheim. This installation had a hydraulic blade angle control device. It was tested over four years up to velocities of 44 m/sec without any damage.

Based on the experience obtained with this test installation, a design for mass production was developed. It had 10 kW installed tower, a tower height of 19.6 meters, the diameter of the three - blade wheel was 9.2 meters and the design rotation rate coefficient was 7. It is shown in Figure 4. The installation was equipped with a two stage spur gear and a differential excitation direct current motor for a nominal net voltage of 110 V. The total weight was two tons. This was the first attempt at a design of a mass produced machine, characterized in particular by the special method of constructing the blades. The blades were built up from simply curved steel sheet shells, and a special point welding procedure was developed to connect the sheets. After the end of the War, these projects were not continued at the Porsche KG.

In Berlin the Reichs working group for wind force (RAW) also wanted to perform their own evaluation of experience with wind force installations. In addition to the theoretical work of Kleinhenz on the most appropriate design of large wind force installations with tower heights up to 250 meters, wheel diameters of 130 meters and installed power levels of 20,000 kW which was to be reached at a wind velocity of 17 meters/sec [5], but which did not lead to any installations being built, the practical work of König and Teubert was also supported by the RAW. G. König at the firm Hein, Lehmann & Co. in Berlin developed electrical wind force installations with wheel diameters of 10 meters and installed power levels of 5 kW, which were subjected to the wind on braced lattice frame towers between 10 and 30 meters in height [6]. König developed a control method in which a very substantial centrifugal force controller was powered by the generator and which displaced the blades around their longitudinal axis by means of direct linkages. By displacing the blades, it was possible for König to limit the fluctuation in rotation rate of the installation to within ± 3%, even for strong gust conditions, provided there was sufficient wind velocity in order to obtain the nominal rotation rate at the corresponding load.

In the year 1932, there was a very popular book written by H. Honnef on the possibility of using the high energy high altitude flow at a height of 200-400 meters above the earth's surface [7]. Honnef concluded from meteorological investigations and from his own observations that wind force installations would have a great potential of being applied for energy conversion if they were sufficiently large and could be built at sufficient heights. The book is essentially only a theoretical work but did much to make the idea of wind energy production popular.

In 1940 he built a test field in support of the government at Bötzow to the Northwest of Berlin, at which large models of his high altitude generating plants were tested. Several installations with tower heights up to 37 meters, wheel diameters up to 9 meters and installed power levels up to 20 kW were tested. These tests were carried out with the ring generators suggested by Honnef, Figure 5. Because of the confusion at the end of the war, parts of his even larger project were lost. /5

F. Teubert at the Gute-Hoffmungshütte also developed fast wind force installations with adjustable blades [8]. His first installation was installed on a tower 33 meters high. It had a four blade wind wheel for 6 kW with a rotation rate coefficient of six and a wing wheel diameter of 8 meters. Later on, an installation for 10 kW with a three-blade wheel having a diameter of 15 meters and a rotation rate coefficient of eight was built on a lattice grid mast 15 meters high, Figure 6.

After the war, the interesting development work was not taken up again.

The developments since 1945

In 1945 D. Stein founded the Nordwind GmbH in Porta Westfalia. He designed and built together with H. Evers a wind force installation with a three-blade wheel having a diameter of 15 meters, a rotation rate ratio of six on a lattice frame tower 20 meters high. In many ways, the control and energy transfer was similar to recent Russian large installations. The outer blades can be deflected for control purposes over 28% of the tip radius. When the nominal rotation rate is exceeded, these are deflected because of their own centrifugal force. This wing tip rotation can only be used for rotation rate control. A system operating with a large delay

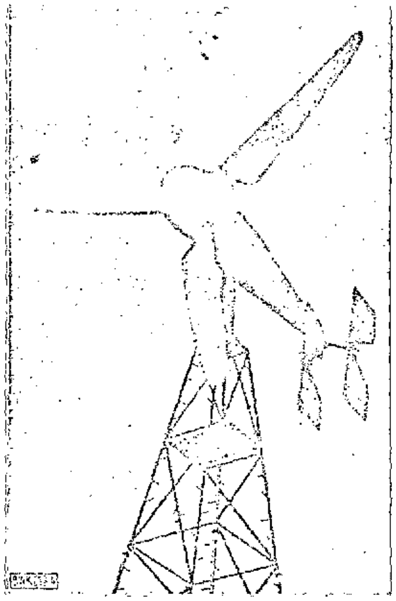

Figure 4. Porsche wind generation installation, 1944 9.2 m diameter, 10 kW.

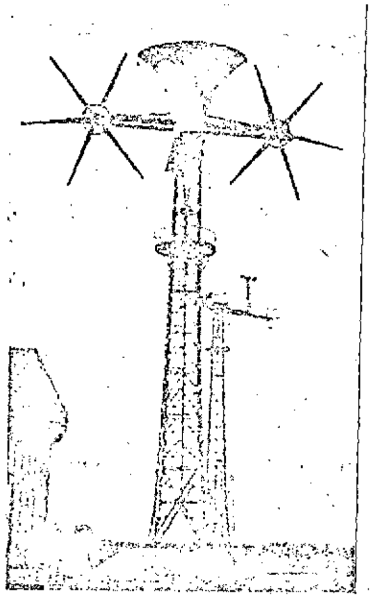

Figure 5. Test field of Honnef at Bölzow near Berlin, 1943

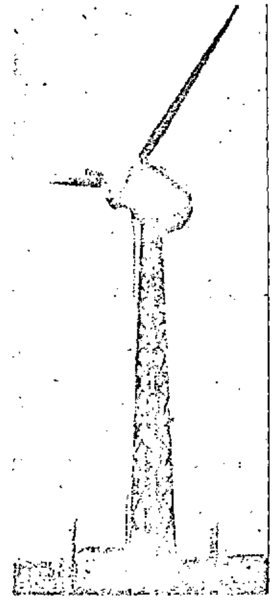

Figure 6. Wind power generation installation Teubert at Fernwald bei Sterkrade, 15 m diameter, 10 kW.

and which is coupled with the directional control of the tower tip gear makes it possible to turn the entire top of the tower out of the wind if the average wind velocity becomes too large. There is a conical wheel gear for driving a vertical shaft which directs the energy from the top of the tower to the ground. There it can be used to drive generators or water pumps, or it can be used for other purposes.

Installations of this type have been extremely reliable over many years under practical situations, Figure 7. For example, the entire North Sea Island Neuwerk in the mouth of the Elbe River including its lighthouse is supplied by such an installation with electrical power. [9]. In the four years since this installation was built, it has produced about 180,000 kWh to satisfy the needs of the island.

Another installation is used as a water pumping station for the Sahara Oasis at Adrar. It has a maximum pumping capacity of 100 m^3/h for a total height differential of over 40 meters. This capacity supplies ample amounts of water to the Oasis with its extensive fruit orchards and palm orchards. At the present time, preparations are being made for additional installations of this type in North Africa and other Sahara Oases.

It was possible for R. Bauer to obtain information on experience with the four-blade 10 kW test installation with a 12 meter wheel diameter and a rotation rate coefficient of eight which he designed in 1924 at the firm Grohmann & Paulsen in Ratzeburg. In 1945, he decided to continue development of wind motors.

New Construction Types

Bauer realized that the economy of wind force installations depends decisively on the total expenditure for construction and therefore on the total weight. This is why he developed a rotor with one blade only. The rotation rate coefficient is 12.6 to 20 depending on the rotor diameter. This exceeds the rotation rate coefficients of the large three-blade Danish F. L. Smidth installations (rotation rate ratio 12). In order to overcome the difficulties associated with the asymmetric force and a possible unbalance of the blade, it rotates freely with a counterweight. The wind wheel shaft was elastic so that the rotor can run freely in an over-critical way, just like the rotor of a Laval-Turbine. The wing is a wind wheel shaft designed like an elastic boom. It rotates at a large distance from the vertical tower axis, so that the rotor adjusts itself to the wind direction, Figure 8, without the necessity for additional devices such as a weather vane.

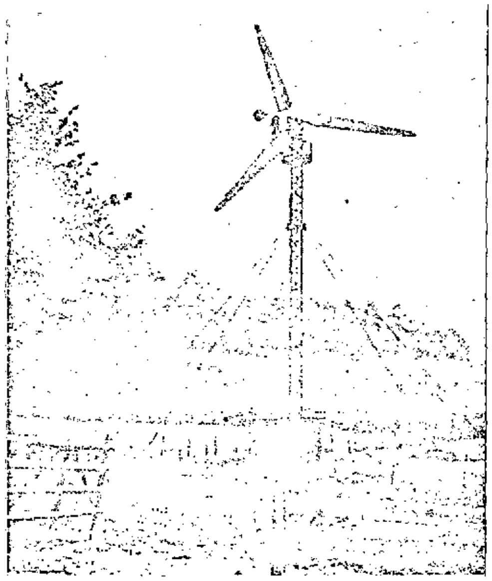

Figure 7. North wind universal wind motor with a 15 m diameter and vertical shaft for energy transfer to be used as a water pump, Marienmünster near Steinheim/Westf.

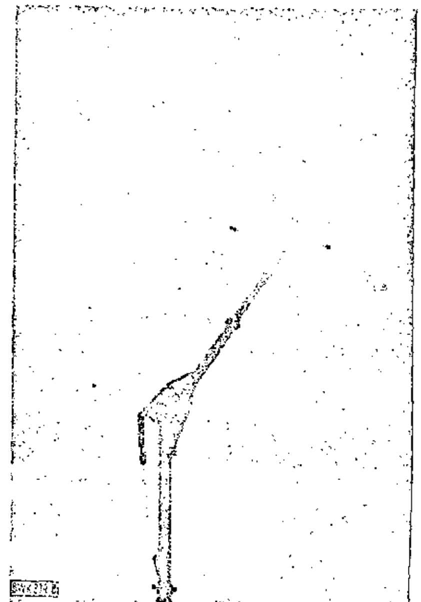

Figure 8. Single blade rotor of R. Bauer. Diameter of the disk swept out by the propellor, 8.6 m, installed power 3 kW.

For control Bauer used a thin upstream wing. Under operating conditions, it is adjusted such that the profile has optimal properties with regard to profile lift-to-drag ratio and maximum lift. On the other hand, when the control system is activated, the upstream wing is rotated so that it destroys the lift of the profile just like a disturbing flap which then negates the force of the wing. In order to stop the installation, a boom shaft is turned upwards in a perpendicular direction, so that the rotor adapts itself to the wind direction just like a weather vane.

This revolutionary construction was first tested with three- /6
meter rotor diameter models. It has been completely developed and has been built by the firm Winkelsträter GmbH since 1952 in Wuppertal, approximately equal to the size of the American wind chargers.

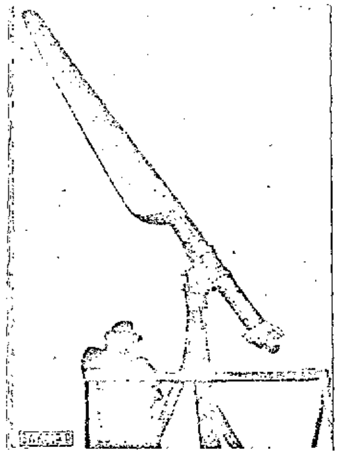

Figure 9. Hütter single blade rotor with air turbine at the wing root and a 600 W generation machine, which is a counterweight, Kirchheim/Teck 1946.

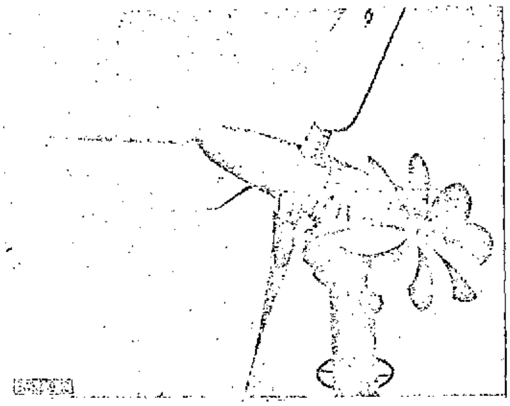

Figure 10. Machine of a 1.3 kW Allgaier test installation with a diameter of 8 m, Ohmden, 1948.

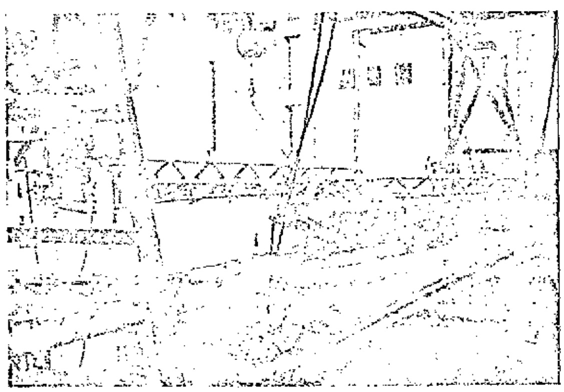

Figure 11. Cooled welding installation for connecting the sheet steel shells, without any warping for the wings of the 10 m diameter Allgaier installation.

After obtaining good results with the small device, work was started on a larger test installation. It has been operating as a test unit since 1949 (Figure 8). The rotor diameter of this installation is 8.6 meters and the rotation rate coefficient is sixteen. The design power level is 3 kW. At the present time a 10-12 meter rotor diameter installation is being developed. Also a 38 meter diameter project for 100 kW is planned.

Because of the development work with wind wheels having high power coefficients [10], the author started the development of a single blade rotor at the firm Schempp-Hirth in Kirchheim/Teck in 1946. This installation is similar to the French Andreau installation [11]. The pressure drop and the flow, which are produced during rotation in the interior region of the wing and which flows from the wing root to the wing tip with an open blade tip, is used to power an air turbine installed in the vicinity of the rotor hub. This turbine shown in Figure 9 is connected directly by means of a short shaft to the current generator, which operates as a counterweight of the single blade rotor. The rotor diameter is six meters and the power is 600 W. The wind wheel disk is oriented with respect to the wind by the free forces of the rotor which rotates behind the tower. Unfortunately this interesting and promising development was stopped because of financial difficulties. The 100 kW Andreau installation*, which is being built in England, proves that this design is promising.

In 1948 the firm Allgaierwerke GmbH, in Uhingen continued the development work, with the purpose of mass production of a suitable standard device. In the summer of the same year, a three-blade test installation having an 8 meter diameter wheel, a design rotation rate coefficient of 8, and an installed power level of 1.3 kW was produced. It is shown in Figure 10. It

* See: The Anemo wind force installation. BWK, Vol. 4, 1952, p. 394.

is mounted on a three leg steel tube mast. In 1949 a test field was built up at Uhingen for carrying out systematic investigations and exact measurements.

A market research project carried out in 1950 in South Africa led to a production of 25 installations. The wheel diameter was 10 meters and the installed power level was 7.2 kW. The design rotation rate coefficient remained the same. During 1951 most of these installations were installed in Southwest Africa, Abyssinia, Argentina and Germany.

In the following years, instead of the original plastic-coated wood construction, the wings were made of steel sheet. The high quality aerodynamic shape was obtained by welding together previously shaped steel sheet shells using point and autogeneous welding techniques as shown in Figure 11.

Control problems

First the control installations were designed similar to those of König and Teubert. Control was achieved exclusively by directly coupled mechanical centrifugal force controllers. This was improved and refined. For mechanical rotation rate limitation, there was a hydraulic and automatic adjustment of the wing blades to the position for which the maximum value of the starting up torque is obtained. It is activated if the installation stops because of extended periods of calm. This installation made it possible to make the devices very light. They began operation at wind velocities which did not produce any significant power production. This means that if the wind increases further, they are capable of taking advantage of even the smallest energy contributions of gusts.

A further improvement consisted of a hydraulic hurricane stopping device. A statistical evaluation of the meteorological data on the time-velocity distribution of the wind during severe storms showed that the observed peak velocities, which could have had a disastrous effect, also occurred during storms, but only over a small percentage of the total time. The dangerous storm gusts are produced extremely rapidly. However, these extremely high power levels corresponding to these velocity peaks are not important for energy production. /7

A hydraulic hurricane stopping device was developed for the Allgai installation. After it is activated during severe gusts, it severely reduces the rotation rate of the installation within fractions of a second. It reaches about 1/3 of the nominal rotation rate after about 1 - 2 seconds. This means that all mass forces and aerodynamic forces are reduced down to between 12 - 15% of the normal values. After the gust has dissipated, the rotation rate and the power level again return to normal values, within a few seconds.

Because of the hydraulic control installation, it is possible to introduce other types of actuators for controlling rotation rate and power level. We took advantage of this possibility because of initial failures using electrically started constant-voltage generators for controlling constant voltage and limiting battery charge current. The newest types have a magnetic valve which is controlled by a voltage measurement bridge. This is an effective and sensitive control for rotation rates. A central switching unit can be used to set any desired limiting voltage, by simply turning a knob on the device. The battery charging process can be controlled simply and reliably by means of adjusting the voltage limit. As is well known, the opposing cell voltage of batteries increases with the state of charging and with the charging current. If a certain charging

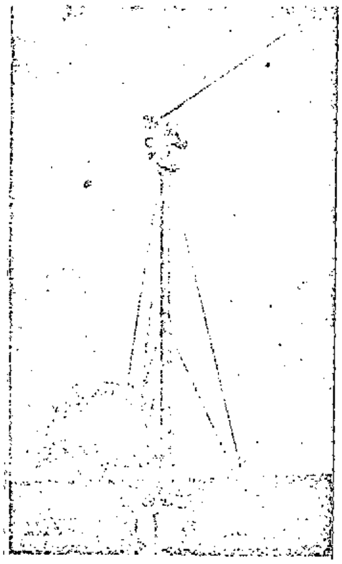

Figure 12. Allgaier standard installation with a 10 m diameter for 6 kW direct current.

current is no longer to be exceeded if a certain charging state has been reached, it is necessary for the charged voltage to remain within certain limits after this time. When the batteries are charged further and for a limited voltage, the charge current will gradually drop. Finally, when the battery is full, it reaches such small values that an equilibrium is established between charging and drain, even for the smallest currents.

In the Allgaier installation, the machines of the installation and the wheel disk swept out by the wing blades are brought into the position of largest power level with respect to the wind in the following way. A small auxiliary wind wheel is installed to the side of the machine and its axis is perpendicular to the wing wheel axis. The same system has been used in Dutch windmills for over 200 years.

The current generator, gears and main supports are collected into one machine unit. The current producer is a connected unit without any intermediate unit. It is attached to the gear housing. No additional coverings are needed.

Since 1951, a pipe tower supported by cables has been used, Figure 12. The diameters of the individual pipe segments are staggered, so that they can be pushed into each other for transportation. The support pipes are stored in the inner pipe.

Installations of this standard type supply sheep farms, grazing farms, farms, worker colonies, lighthouses, mountain barns and FM relay stations all over the world. They have proven themselves well under all possible climatic conditions, such as dust storms, under conditions with moist sea air, under very hot conditions and under conditions with snow and ice.

The yearly total production in Germany at the present time of all installations which are operating is between 250,000 to 300,000 kWh.

Energy Supply to Public Electrical Networks

In the fall of 1949 the study group for wind force was founded in Stuttgart. This is a neutral organization involving all groups associated with wind energy production in West Germany. The society caused Federal agencies, public electricity companies as well as business and industry to become interested in wind energy. Available measured wind values were evaluated on a broad basis in collaboration with the German meteorological service in Frankfurt/Main. A neutral advisory group was formed. Prolonged operational tests, with several wind force installations connected to public electrical networks, were carried out. A unit having an installed power level of 100 kW to feed public electrical networks was designed. At the present time there is a study group for evaluating four projects of this type.

In the summer of 1952, three phase current was fed to the 10 kV line of the Neckar generating plant near by. This was done from the test field of the firm Allgaier using a 10 meter standard installation, equipped with a 8.8 kVA asynchronous generator. The wind variation and the electrical energy were recorded continuously by the AEG/Ferrari fixed quantity recording devices. At the end of the experiment, we were able to establish relationships for the behavior of the wind force installation while operating in parallel with a public electrical net [13]. The results were so promising that the experiment is now being continued in a region having more favorable wind conditions, that is, at Büsum on the German North Coast. We plan a very long experiment duration.

Similar experiments were already carried out at the beginning of the 30's, using a three-blade 100 kW installation at Balaklava on the Crimea penninsula [14] in 1940/43 by the Ventimotor GmbH in Weimar. Between the years 1940 and 1943 experiments with a 1,000 kW unit were carried out at Grandpa's Knob in Vermont, USA [15]. Juul carried out experiments between June 1950 up to August 1951 at Egesborg in Denmark using a 12 meter diameter installation [16].

All of these experiments had positive results. This occurred even though some specialists had predicted that parallel operation would be difficult because of the fact that the wind conditions were non-uniform. On the other hand, M. Kloss [17] already in 1942 showed that parallel operation in conjunction with large tact-producing nets is possible using synchronous generators, and the operational conditions would have to be very stable. In 1947 the author showed [18] that, in spite of the greatly fluctuating wind velocity, the total energy yield of a wind force installation operating in parallel with a net could amount to 96% of the theoretical optimum if the wind frequency distribution is taken into account. These predictions were also confirmed by experiment. It is therefore possible to operate a wind force installation at a constant rotation rate in spite of greatly fluctuating wind velocity, if the rotation rate-load behavior or the frequency-load behavior of the machine driven by wind wheels will operate under partial load conditions. This means that when the frequency drops under a certain value no more load is accepted by the driven machine, because of the values specified by the generator slip. This is the case for parallel operation.

Aerodynamic problems. /8

The wheel which is free to rotate in the air stream reaches a power optimum based on the rotation rate coefficient specified by the design. For rotation rate coefficients which are above this optimum value, the dimensionless power coefficient — the power characteristic number — gradually drops off. As the rotation rate coefficient is increased, it drops off sharply. At a certain value of the rotation rate coefficient, it has the value zero as shown in Figure 13.

This value of the rotation rate coefficient which is reached for a turbine operation amounts to about twice the design rotation rate coefficient, according to experience. For rotation rate coefficients which are below the design value, the power coefficient also drops off slowly. Later on, if the flow separates from the blade, it drops off very rapidly. It is only because of the blade twist that the separation of the flow does not occur over the entire blade length. This means that even for a small rotation rate coefficients there is a small residual torque, which makes the wheel start if it is standing still, provided that the aerodynamic torques are greater than the friction torques.

Under realistic operational conditions, and if the wind wheel reduction gears and powered machine are designed properly, operational conditions will occur which are close to the optimum value of the power coefficient. Because of the flat optimum, it is possible to have quite substantial deviations from the

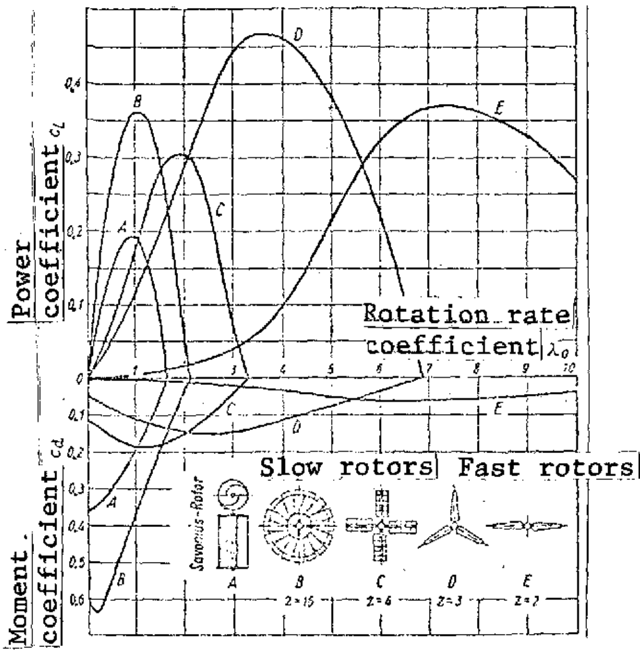

Figure 13. Relationship between the power coefficient and the rotation rate coefficient of wind turbines of various designs according to Fateew.

design "coefficient" in both the positive and negative directions, without any significant losses.

If the rotation rate is fixed, a drop in the wind velocity results in an increase in the rotation rate coefficient and vice versa. If the system is properly tuned to the frequency distribution of the individual wind velocities, which is to be expected at the place where the installation is installed, only a very small loss occurs in the total energy balance compared with the theoretical optimum, which corresponds to operation using a power coefficient at all operational states. In general, this loss does not exceed 4 - 7%.

Wind wheel size and economy.

The economy of wind force installations is a question of size, just like all other force machines. In order to obtain units with reasonable power output levels, the circular area subjected to the wind must be higher than a certain minimum. According to German experience, a circular area between 40 to 70 m^2 is a minimum for the relatively favorable frequencies in good wind areas. This is necessary in order to supply a residential area.

For small residential areas, small professional and industrial complexes, radio stations, lighthouses, average hotels, etc. wheel circle areas between 80 - 200 m^2 are recommended for saving energy. reasons.

The dimensions can never be too large for supplying public electrical networks. This is not the case if the supply is an addition to the water and thermal power plants, as is presently being done in Ireland by the Electricity Supply Board.

Considering the continuity of the development, the risk and the methods of fabrication, the units to be installed will have circular areas between 400 and 1,000 m^2. Of course, it would be possible to increase the area to several thousand square meters of circular area.

It can easily be seen that there is a requirement for ever-increasing power levels. In such installations, the problem of converting the energy of the wheel into energy for the generator increases in importance. Investigations have shown that, especially for large installations, the fractional cost of the gears as well as the percentage of the gear weight is substantial. The price and the weight of the gear depend essentially on the drive shaft rotation rate for a given power level. If the wind wheel diameter and wind velocity are specified, the drive shaft rotation rate is proportional to the rotation rate coefficient. This is why advanced designers are attempting to increase the rotation rate of large wheels.

Rotation Rate

High rotation rates are only possible by refining the wheel aerodynamics. This is why it was not possible to develop rapidly rotating wheels until the beginning of the 20th century.

Recent experience in lifting wing flow theory and air screw theory makes it possible to increase the rotation rate coefficient of large wheels to very substantial values.

This development is not limited by the power loss at high rotation rate coefficients due to the drag of the blade profiles, as one would expect. Instead, it is difficult to obtain static and dynamic control of the wing blades, which become very thin at the high rotation rate coefficients. If the blade width is expressed as a percentage of the radius at the corresponding blade station, we obtain the following ratio of blade with t to radius R for various rotation rate coefficients:

Rotation rate coefficient		1	2	3	6	8	12
t/R	%	120	40	11	6	3	1,3

The required blade width at a rotation rate coefficient of 12 is only 1/100 of the value required for the rotation rate coefficient of one.

Practical experience obtained over long periods has shown that any increase in the rotation rate coefficient of wheels with wings by even small steps leads to enormous difficulties and penalties. The problems associated with the high circumferential velocities are usually solved in a completely new way. New solutions for control and blade suspension are found. This characteristic feature of the development is similar to the /9
development of water turbines and thermal generating units.

We believe that the present state of technology corresponds to rotation rate coefficients between 8 and 12. The wing wheel proportions which are obtained at these values are similar to dimensions which characterize the lifting propellors of modern

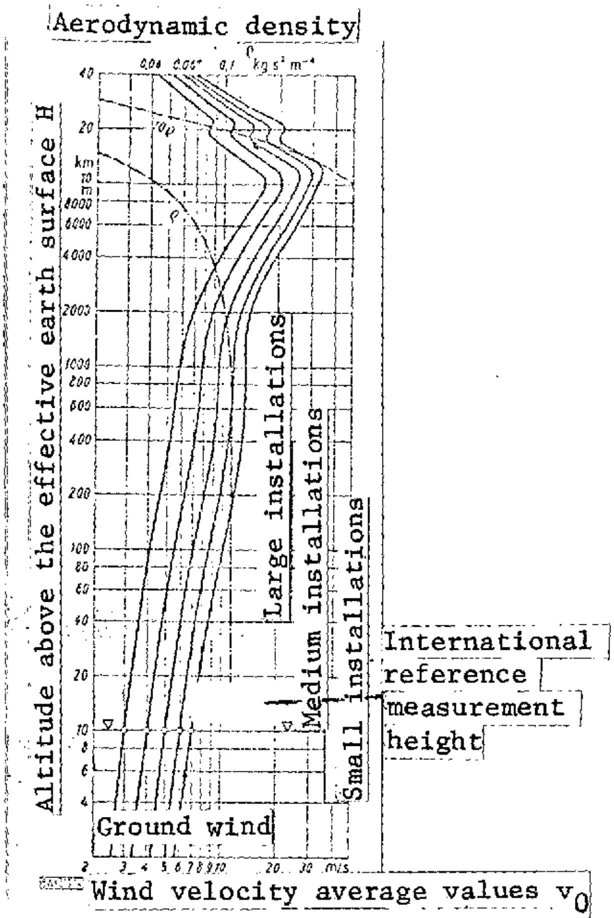

Figure 14. The wind velocity-altitude variation referred to average values at a height of 10 m.

helicopters. We believe that it will only be possible to further increase the rotation rate coefficient by a substantial research effort. One can clearly predict wind force installations with dimensions which are considerably greater than anything built at the present time. We expect that within a few years such installations will be used as energy sources for supplying individual units as well as for supplying public electrical networks.

Practical application of wind force installations

In any investigation of economy, the two characteristic applications already mentioned must be treated completely separately:

a) Installations for supplying remote consumers, not connected with public electrical network and,

b) Installations for supplying the available networks.

The size of the unit to be used for remote consumers will have wheel circular areas between 40 and 200 m^2. The installed power levels will lie between 3 - 30 kW. The economy of these installations only competes with units driven by crude oil. The wind force installations as well as diesel units require a device for energy equilization. This is because there will not be a uniform requirement limited in time. There also will not be a requirement which is the same at all times. The economy of diesel units drops considerably if the unit must remain in operation even when very little power is being drawn off. Even in Germany where the public electrical networks are very branched and dense, there are consumer groups which are interested in their own supply. We have found that, even if a diesel unit is already available, there is considerable interest in wind force installations, in order to save the high continuous costs of diesel operation. A very simple calculation shows that if the lifetime of a wind force installation is only 5 - 8 years, it is more economical than a diesel unit having the same power output. We must consider the fact that wind force installations manufactured up to the present have only been built in small quantities. Diesel units have been built in very large production quantities. Therefore there is no doubt that for the same manufacturing conditions and after overcoming some difficulties which are the result of the new technology, wind force installations will be considerably more economical than small thermal units. This means that a certain minimum lifetime must be guaranteed and a large service organization must be built up in areas which have favorable wind conditions.

In the case of supplying public electrical networks, there is no requirement for immediate energy equilization. For this purpose, the units must be much larger than the installations developed for individual consumers. This is why the effort for controlled functions can be considerably higher. This would mean that a completely independent mode of operation requiring no maintenance could be developed.

The investigations of the British Electrical Research Association in London and the Electricity Supply Board in Dublin at the British and Irish North, Northwest and Southwest coasts have shown that, if the location is properly selected on free standing hills in the vicinity of the coast, one may expect average yearly wind velocities between 9 and 11 m/sec. Economy can already be proven at these large average values, even for very small units designed for individual consumers, which have already been built in small numbers. Such installations with less than 100 m^2 wheel circular area produce 480 to 520 kWh per year and per square meter of wheel circular area. This means that an installation having 500 m^2 wheel circular area, which are the dimensions of a large Dutch windmill, could supply about 250,000 kWh/year to a public electrical network.

The energy contained in the wind.

The question of the available total energy arises in discussing the problem of whether wind force machines should be applied to supplement hydroelectric and thermal generating sources for public electrical networks. It can be estimated from the energy density of the solar radiation. The total power of the energy radiated by the sun to the earth is $1.694 \cdot 10^{14}$ kW or $1.484 \cdot 10^{18}$ kWh/year. Well known meteorologists such as Süring [19] estimate that 2.5% of the total radiated sun energy is converted into energy of motion of the entire atmosphere. /10

The literature contains the results of many measurements of the velocity distribution of the air flow at various altitudes above the earth's surface, up to the stratosphere. This is shown in Figure 14. From these values, we can estimate not only the kinetic energy of the entire atmosphere as $2.5 \cdot 10^{14}$ kWh but we can also estimate the power which maintains the motion against ground friction and internal friction of the air masses which pass each other at various velocities. The order of magnitude of the Reynolds numbers of the air masses moving over the earth surface can be estimated to be between 10^{11} to 10^{12}. This can be estimated from the way in which the low pressure and the high pressure areas move. Using the ground roughness magnitudes, it is possible to estimate the surface drag coefficients for the ground and ocean areas. The values of the velocities used in the calculation correspond to the value which is measured in an altitude range between 200 to 300 meters.

With this model, we find that the total power level required to overcome the ground friction and the internal friction of the air is approximately 10^{12} kW. This is on the order of the fraction of the total radiation power estimated by Suering.

The greatest part of these energies is contained in the extremely fast high altitude flow about 8,000 to 14,000 meters above the earth's surface. The velocity is between 18 and 26 m/sec. At the present time this cannot be taken advantage of. However, from the altitude distribution of the velocity, we can derive the fraction of the total flow energy which can be exploited. This fraction increases with the density of large wind force installations over the earth's surface. Because of mixing processes known as turbulence from aerodynamics, energy is supplied from the higher layers to the lower layers during the strong braking of the lower atmosphere. This means that it will be possible to exploit the large flow energies contained in average height flows by a sufficiently dense network of ground generating stations, and it will not be necessary to build very high wind force stations. The types of installations can be seen from work which has been in progress for many decades in the USA, Russia, Denmark, France and Germany. We can assume

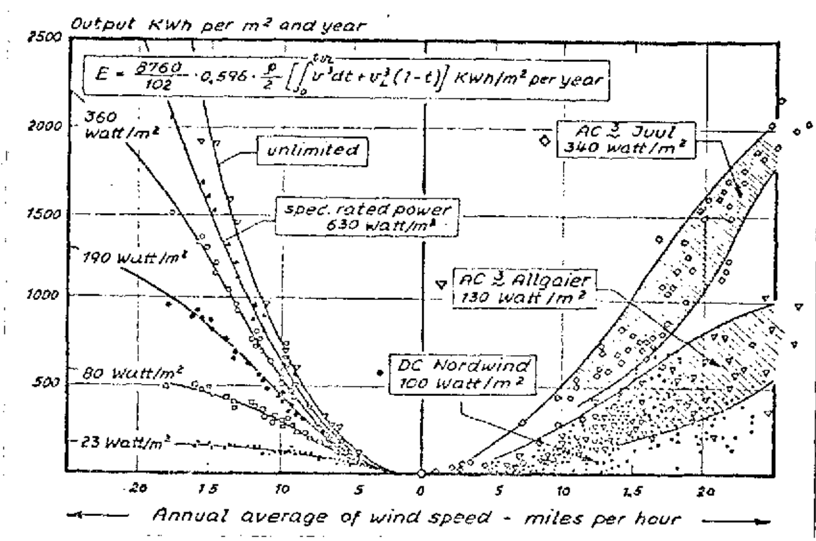

Figure 2.

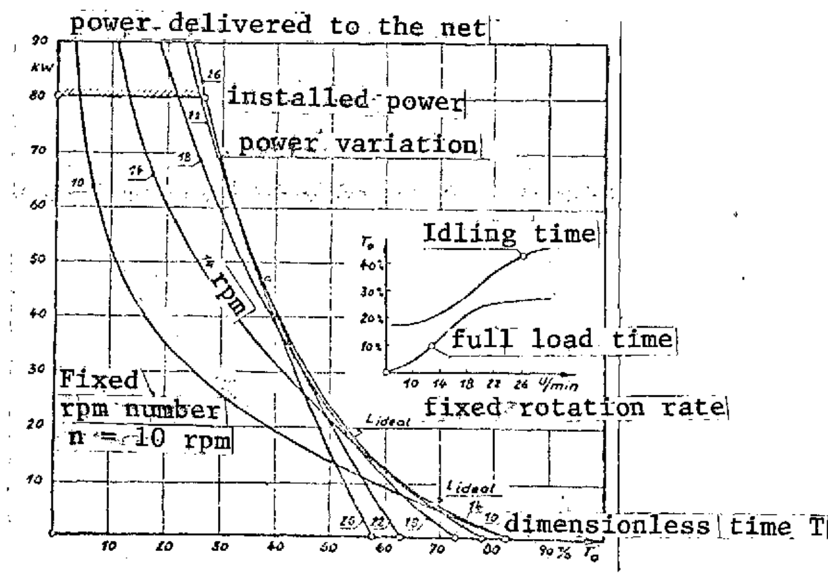

Figure 3.

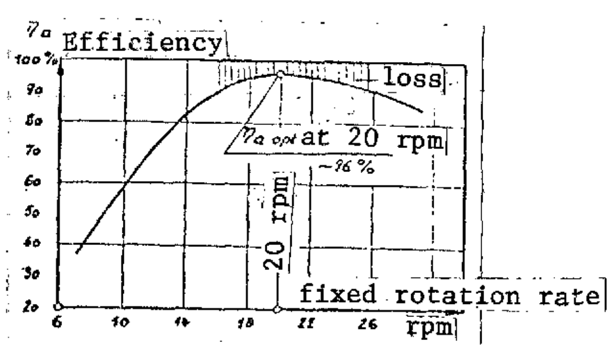

Figure 4.

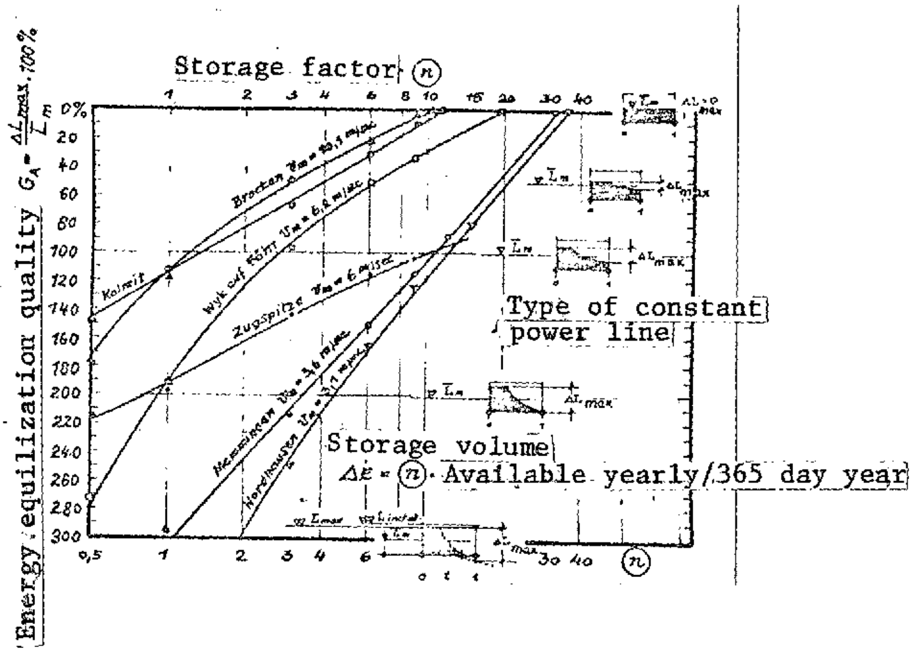

Figure 5.

Translator's Note: Other words refer to geographical locations.

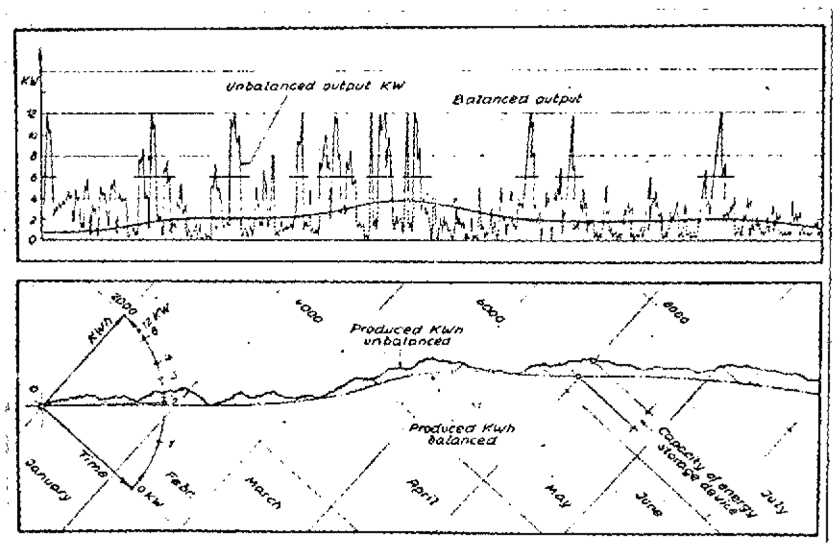

Figure 6.

that if this research is continued, wind energy will come into wide spread practical application, after a development period of several decades, just like the development of helicopter technology.

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